A mechanism for the loading-unloading substorm cycle missing in MHD global magnetospheric simulation models

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[1] A 2-dimensional numerical driven current-sheet model has been developed that incorporates an idealized current-driven instability with a resistive MHD system. Under steady loading, the model exhibits a global loading-unloading cycle. The specific mechanism for producing the loading-unloading cycle is discussed. It is shown that scale-free avalanching of electromagnetic energy through the model, from loading to unloading, is carried by repetitive bursts of localized reconnection. Each burst leads, somewhat later, to a field configuration that is capable of exciting a reconnection burst again. This process repeats itself in an intermittent manner while the total field energy in the system falls. The total field energy is reduced to well below that necessary to initiate an unloading event and, thus, a loading-unloading cycle results. It is shown that, in this model, it is the topology of bursty localized reconnection that is responsible for the appearance of the loading-unloading cycle. **Citation:** Klimas, A. J., V. M. Uritsky, D. Vassiliadis, and D. N. Baker (2005), A mechanism for the loading-unloading substorm cycle missing in MHD global magnetospheric simulation models, *Geophys. Res. Lett.*, *32*, L14108, doi:10.1029/2005GL022916.

1. Introduction

[2] Global MHD magnetospheric simulation models are often driven by real or modeled solar wind data. Following a southward turning of the incoming interplanetary magnetic field (IMF) these models may simulate a single substorm. Under continuing dayside merging, however, these models invariably evolve into a quasi-steady directly-driven state characterized by continuous reconnection in the tail at a rate that is in equilibrium with that of the dayside merging; a quasi-steady throughput of magnetic flux results [e.g., see *Lopez et al.*, 2001; *Goodrich et al.*, 1998]. This behavior is in marked contrast to that of the real magnetosphere. During the passage of an interplanetary magnetic cloud, for example, the IMF may turn strongly and quasi-steadily southward for an extended period during which an intermittent sequence of strong substorms is typically observed embedded within an interval of magnetic storm activity [*Wu et al.*, 2004]. This characteristic behavior - the substorm cycle - cannot be simulated by available global MHD models. Given the central role that MHD models presently play in the development of our understanding of magnetospheric dynamics, and given the present plans for the central role that these models will play in ongoing space weather prediction programs, it is clear that this failure must be corrected.

[3] The substorm in the magnetotail is hysteretic: Magnetic flux is added to the tail until the threshold of a still-undetermined instability in the tail is reached at which point unloading begins with the onset of a substorm. Magnetic flux is then unloaded to a level well below that which was necessary to reach the instability threshold; thus, the threshold for quenching this instability is well below that of its excitation. The substorm growth phase follows one dynamical path while the expansion and recovery phases follow another. Under steady loading conditions these paths close to form a hysteretic loop that is traversed repeatedly to produce the substorm cycle.

[4] The hysteretic substorm cycle must be incorporated into global MHD magnetospheric simulation models. The way in which this is done, however, should not contradict known properties of the magnetotail dynamics. *Uritsky et al.* [2002, 2003], through an investigation of a large number of consecutive auroral images obtained by the UVI experiment on the Polar spacecraft, have shown that regions of bright night-side auroral emission exhibit many of the properties of scale-free avalanching models of self-organized criticality (SOC). Uritsky et al. and *Klimas et al.* [2004] have suggested that these properties of the auroral emissions are a reflection of the dynamics of the magnetotail. They have suggested that the transport of magnetic flux through the tail, from loading to unloading, is carried by avalanches of localized reconnection that exhibit scale-free statistics. Thus, we are led to consider modifications of the global MHD magnetospheric simulation models that are consistent with this explanation and also lead to a loading-unloading substorm cycle.

[5] The scale-free probability distributions obtained by *Uritsky et al.* [2002, 2003] impose substantial restrictions on MHD model modifications that might be considered. The distributions show no characteristic scales over the time-scale range from a few tens of seconds to several hours and over the length-scale range, when the auroral scales are mapped into the tail to $\sim$20 R_E, from $\sim$1 R_E up to global tail dimensions. Whatever mechanism might be invoked to induce a loading-unloading cycle, it cannot introduce characteristic scales into the system dynamics over these ranges. Since these ranges essentially cover those over which the MHD simulation models are considered valid approximations, we are led to consider the possibility that the mechanism lies at kinetic or micro-turbulence scales, well below the valid MHD scales.

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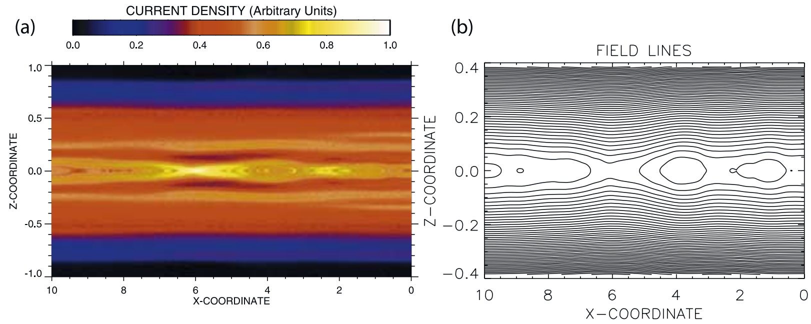

Figure 1. Current density in arbitrary units (a) and associated magnetic field configuration (b) at the end of a loading interval, just before the onset of an unloading interval due to the excitation of the current-driven instability at the position of the x-line at $x \simeq 6$ and $z = 0$. The field direction is antisymmetric about $z = 0$. Notice that only a portion of the field configuration is shown.

[6] *Klimas et al.* [2004] have developed a 2-dimensional numerical driven current-sheet model that incorporates an idealized representation of a current-driven instability into a resistive MHD system. The instability is excited when and where the MHD current density exceeds a critical threshold and its excitation leads to the growth and saturation of an anomalous resistivity-producing wave-field. The resistivity so generated is fed back into the resistive MHD system. These kinetic and micro-turbulence components of the model are adapted from *Lu* [1995] and, following a suggestion given by Lu, the idealized current-driven instability is assumed hysteretic; the threshold for quenching the instability is assumed to be slightly below the threshold for exciting it. Klimas et al. have shown that this hysteresis leads directly to a global loading-unloading cycle in the model and to scale-free avalanching in the transport of electromagnetic (primarily magnetic) energy through the model. The avalanche statistics are similar to those of the auroral emission regions; the ranges of scales and power-law indices in the auroral distributions are well represented.

[7] The specific mechanism for producing the loading-unloading cycle in the 2-D driven current-sheet model is explained in this paper. We show that the scale-free avalanching of electromagnetic energy through the model is carried by repetitive bursts of localized reconnection. Each burst of localized reconnection repeats itself in an intermittent manner while the total field energy in the system falls to well below that necessary to excite the initial reconnection event. In this manner, the field energy is reduced to well below that necessary to initiate an unloading event before the unloading event ceases and thus a hysteretic loading-unloading cycle ensues.

2. Driven Current-Sheet Model

[8] The driven current-sheet model under consideration here is described fully by *Klimas et al.* [2004]; it contains a 2-dimensional resistive MHD base component plus idealized kinetic and micro-turbulence components that have been adapted from *Lu* [1995]. The excitation and quenching of a current-driven instability are governed by

$$Q(|J|) = \begin{cases} D_{\min} & |J| < \beta J_c \\ D_{\max} & |J| > J_c \end{cases} \tag{1}$$

in which J is the scalar current density, J_c is a critical current density, and β is a number less than, but close to, the value one. At any position on the simulation grid, the quantity Q can take on one of the two values, $D_{\max}$ if the current density exceeds J_c, or $D_{\min} \ll D_{\max}$ if the current density consequently falls below βJ_c. The transition from $D_{\min}$ to $D_{\max}$ represents the excitation and saturation of the current-driven instability over a time-interval that is below the resolution of the simulation and thus enters as an instantaneous transition; the transition from $D_{\max}$ to $D_{\min}$ represents the consequent quenching of the instability. The effects of excitation or quenching of this idealized instability are introduce into the model through

$$\frac{\partial D(z,t)}{\partial t} = \frac{Q(|J|) - D}{\tau} \tag{2}$$

in which D is a dimensionless anomalous resistivity, which enters the MHD component of the model as diffusivity, and τ represents a single time-scale for both the growth and decay of the resistivity in this simple model.

3. Simulation Results

[9] Under steady loading, the current-sheet model exhibits a loading-unloading cycle. During loading intervals the evolution of the system is essentially ideal MHD. During unloading intervals the model components (1) and (2) are activated and complex patterns of resistivity D are generated. Examples of this behavior are discussed by *Klimas et al.* [2004].

3.1. Unloading Initiation

[10] Figure 1 illustrates the current and field-line distributions that have developed at the end of a loading interval, just before the initiation of unloading. Plasma, containing frozen-in magnetic flux in opposing directions has been steadily driven into the simulation region from above and below during this loading interval. Since the end of the last unloading interval, the current distribution has been thinned somewhat and the strengths of the field reversal and the supporting current distribution have been increased. For this particular case $J_c = 0.8$ and it can be seen that there is a small region in the current distribution that has almost reached this value; the unloading interval that ensues begins

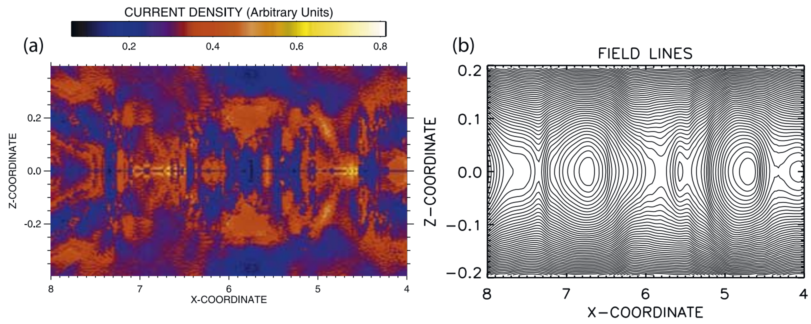

Figure 2. Current density in arbitrary units (a) and associated magnetic field configuration (b) at an instant within an unloading interval just before the current filament at the position $x \simeq 4.6$ and $z = 0$ reaches the critical value $J_c = 0.8$ and excites the current-driven instability. The current filament at $x \simeq 6.6$ and $z = 0$ will become unstable shortly thereafter. The field direction is antisymmetric about $z = 0$. Notice that only portions of the current distribution and field configuration are shown.

with a single reconnection site in this high current region. The evolution of these distributions that follows can be viewed in two animations (J_start.mpg and FL_start.mpg) that have been included as auxiliary material[1]. The evident excitation and propagation of current-sheet waves have been discussed by *Klimas et al.* [2004].

3.2. Unloading Persistence

[11] Unloading in this current sheet model consists of a rapid cascade of electromagnetic energy through the plasma from the vicinities of the upper and lower boundaries of the simulation grid, where the energy is introduced to the system, into the central region of the grid where the magnetic field is annihilated and the energy is converted to thermal and kinetic energy. This cascade is enabled by the excitation of the current-driven instability and the consequent generation of diffusivity in the MHD plasma that allows the magnetic flux to slip through the plasma into the central neutral region. This cascade has been shown to exhibit scale-free avalanching statistics over large ranges of time, size, and energy scales [*Klimas et al.*, 2004]. Here we show that the cascade is carried by intermittent sequences of localized reconnection bursts. Further, we show that these sequences have the remarkable property that they are self-sustaining and, thus, are able to persist long after the total field energy in the system has been reduced to well below that necessary to initiate the unloading process in the first place.

[12] Figure 2 shows some details of the distributions of current and field lines that have developed later in the unloading event whose initiation was discussed above. The field, in the central reversal region, is dominated by two "bubbles" that are supported by current filaments whose strengths are just below the critical value $J_c = 0.8$. The evolution of field and current and resistivity densities can be viewed in the auxiliary animations FL_mid.mpg, J_mid.mpg, and D_mid.mpg, respectively. The details shown in Figure 2 occur near the beginning of those animations. It can be seen that the magnetic bubbles are destroyed by field-line merging following the excitation of the current-driven instability at the sites of the current filaments and the consequent propagation of current-sheet waves away from the positions of the filaments. Later, however, the bubbles and supporting current filaments can be seen to reform, thus setting the stage for a repetition of this destruction and reformation process. Many cycles in this quasi-periodic process can be seen to lead to the overall transport of magnetic flux into the central reversal region where it is annihilated.

[13] Figure 3 shows further details of the magnetic bubble on the right side of Figure 2 at two instants within a single destruction and reformation cycle. The panels of Figure 2 have been taken from an animation (auxiliary material FL_detail.mpg) that shows the evolution of this bubble over the course of somewhat more than one cycle. The evolution of the associated current and resistivity densities can be viewed in the auxiliary animations J_detail.mpg and D_detail.mpg respectively. From Figure 3 and the animations it can be seen that the initial destruction of the bubble leads to the propagation of a pair of x-lines away from the site of the current filament; the x-lines remain just behind a pair of current-sheet waves that propagate away from the filament site. Field lines reconnect at the positions of the x-lines and consequently they wrap around the magnetic bubble, thereby rebuilding the bubble and strengthening its supporting current filament. This

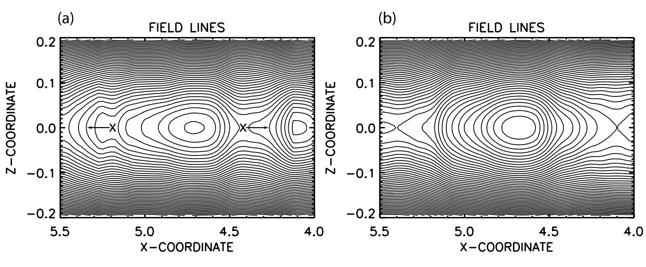

Figure 3. Further details of the magnetic bubble on the right side of Figure 2 earlier (a) and later (b) within a single destruction and reformation cycle. The approximate positions of a pair of propagating x-lines are shown in panel (a). The later positions in panel (b) are self evident. Field-line reconnection at the positions of the x-lines leads to the regeneration of the magnetic bubble. The field direction is antisymmetric about $z = 0$. Notice that only small portions of the field configurations are shown.

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL022916.

process continues until the current filament strength reaches the critical current strength, the current-driven instability is excited, and a new cycle begins with another burst of reconnection.

4. Discussion

[14] We have demonstrated a specific mechanism for the creation of a global loading-unloading cycle in a driven current-sheet model that has been designed to study the dynamics of the plasma sheet. In this model, the loading-unloading cycle is a consequence of the topological properties of localized reconnection sites that emerge during unloading events. At these sites, localized reconnection starts at the position of a strong current filament. Initially, the current filament is destroyed but the subsequent evolution of the reconnection site then regenerates the current filament, thus setting the stage for the next localized reconnection burst at that site. This process repeats in an irregular fashion, sometimes in pairs of sites as shown here and sometimes at single sites. The positions of the sites are relatively stable but the sites do move, fade away, and reemerge at different positions in a irregular fashion over the lifetime of an unloading event. Only a very short sample of this evolution has been discussed here but the behavior that can be seen in the auxiliary animations is typical and can be found during any of the many unloading intervals that have been simulated.

[15] During unloading, as the field energy declines, the isolated current filaments continue to emerge and disperse as described in the preceding paragraph. The filaments can be strong enough to initiate reconnection but they are too limited in spatial extent to contribute significantly to the overall current sheet strength. Thus, the overall strengths of the field reversal and its supporting current sheet can decline to well below the values that led to the unloading event initiation while, even so, the relatively strong sporadic current filaments persist and field annihilation continues. When, for reasons that we do not understand at present, this unloading process ceases, an extended loading period is then necessary to bring the overall current sheet back to the level necessary to initiate the next unloading phase.

[16] The topological features of a reconnection site that lead to the regeneration of its associated current filament are created by the expansion of current sheet waves away from the site of the filament. It has been shown [*Klimas et al.*, 2000] that the existence of the current sheet waves depends on the hysteresis in the idealized current-driven instability (1). Thus, in this model the hysteresis of the global loading-unloading cycle has its source at the kinetic level, below the resolution of the MHD model component, and its existence is compatible with the scale-free avalanche distributions of this model. Consequently, these model distributions remain a potential explanation for the scale-free auroral avalanche distributions discovered by *Uritsky et al.* [2002].

[17] At present, we are unaware of any direct evidence either for or against our assumption of hysteresis in current-driven instabilities that may be relevant in the plasma sheet environment [e.g., see *Lui et al.*, 1995, and references therein]. However, the behavior of the driven current-sheet model under consideration here provides indirect evidence in favor of this assumption: (1) the current-sheet model provides a potential explanation for the plasma sheet scale-free avalanching inferred by the observed auroral dynamics; (2) the model can include a loading-unloading cycle in its evolution; and (3) the presence of hysteresis in the current-driven instability leads directly to bursty localized reconnection.

[18] The current-sheet model is very limited and can be considered to represent, in an idealized 2-D fashion, only a small portion of the plasma sheet. There is no way to differentiate open from closed flux in this model. Because there is no solar wind at the boundaries of the model, "unloading" is due almost entirely to merging and annihilation, not plasmoid release. Clearly, this model will require many refinements as well as an extension to 3-dimensions before it will be presented as a plasma-sheet model. We suggest that the bursts of localized reconnection observed in the present model are likely to evolve, when the refinements and extension are accomplished, into the bursts that make up the bursty bulk flows observed in the plasma sheet. It may be possible, then, to show that the loading-unloading substorm cycle of the magnetosphere is a consequence of the localized and self-sustaining nature of reconnection in the tail.

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